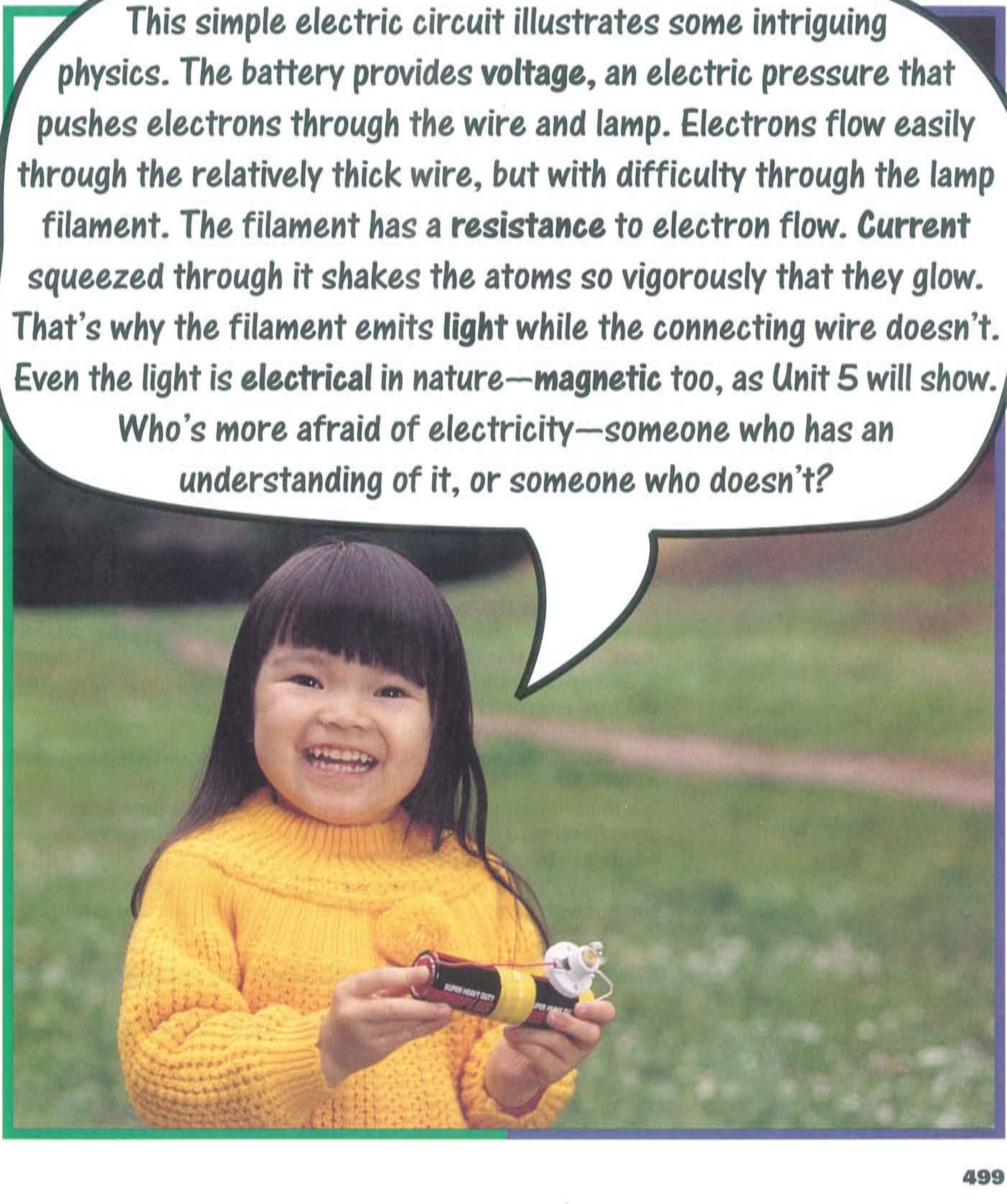
V Electricity and Magnetism



32 Electrostatics

ormous transfer of electrical
ergy.

This chapter develops the fundamentals of electric phenomena, and is basic to chapters that follow.

Electricity in one form or another underlies just about everything around you. It's in the lightning from the sky; it's in the spark beneath your feet when you scuff across a rug; and it's what holds atoms together to form molecules. The control of electricity is evident in technological devices of many kinds, from lamps to computers. In this technological age it is important to have an understanding of how the basics of electricity can be manipulated to give people a prosperity that was unknown before recent times.

This chapter is about **electrostatics,** or electricity at rest. Electrostatics involves electric charges, the forces between them, and their behavior in materials. The next chapter is about the aura that surrounds electric charges—the *electric field.* Chapters 34 and 35 cover moving electric charges, or *electric currents;* the voltages that produce them; and the ways that currents can be controlled. Finally, Chapters 36 and 37 cover the relationship of electric currents to magnetism, and how electricity and magnetism can be controlled to operate motors and other electrical devices.

An understanding of electricity requires a step-by-step approach, for one concept is the building block for the next. So please study this material with extra care. It is a good idea at this time to lean more heavily on the laboratory part of your course, for *doing* physics is better than only studying physics. If you're hasty, the physics of electricity and magnetism can be difficult, confusing, and frustrating. But with careful effort, it can be comprehensible and rewarding.

deotape: Show "Electrostatics" m the series *Conceptual ysics Alive!* Note sequence demonstrations—how one ds to the other.

portant Terms

arge
ctrical force
ctrostatics

ow attraction and repulsion h fur, rubber, and plastic ls, and pith balls—or equiva- t apparatus. One demo is rth a thousand words.

32.1 Electrical Forces and Charges

You are familiar with the force of gravity. It attracts you to the earth, and you call it your weight. Now consider a force acting on you that is billions upon billions of times stronger. Such a force could compress

you to a size about the thickness of a piece of paper. But suppose that in addition to this enormous force there is a repelling force that is also billions upon billions of times stronger than gravity. The two forces acting on you would balance each other and have no noticeable effect at all. It so happens that there is a pair of such forces acting on you all the time—**electrical forces.**

Electrical forces arise from particles in atoms. In the simple model of the atom proposed in the early 1900s by Ernest Rutherford and Niels Bohr, a positively charged nucleus is surrounded by electrons (Figure 32.2). The protons in the nucleus attract the electrons and hold them in orbit, just as the sun holds the planets in orbit. Electrons are attracted to protons, but electrons repel other electrons. This attracting and repelling behavior is attributed to a property called **charge.*** By convention (general agreement), electrons are *negatively* charged and protons *positively* charged. Neutrons have no charge, and are neither attracted nor repelled by charged particles.

Some important facts about atoms are

1. Every atom has a positively charged nucleus surrounded by negatively charged electrons.
2. All electrons are identical; that is, each has the same mass and the same quantity of negative charge as every other electron.
3. The nucleus is composed of protons and neutrons. (The common form of hydrogen, which has no neutrons, is the only exception.) All protons are identical; similarly, all neutrons are identical. A proton has nearly 2000 times the mass of an electron, but its positive charge is equal in magnitude to the negative charge of the electron. A neutron has slightly greater mass than a proton and has no charge.
4. Atoms usually have as many electrons as protons, so the atom has zero *net* charge.

Just *why* electrons repel electrons and are attracted to protons is beyond the scope of this book. At our level of understanding we simply say that this is nature as we find it—that this electric behavior is fundamental, or basic. The fundamental rule at the base of all electrical phenomena is

Like charges repel; opposite charges attract.

The old saying that opposites attract, usually referring to people, was first popularized by public lecturers who traveled about by horse

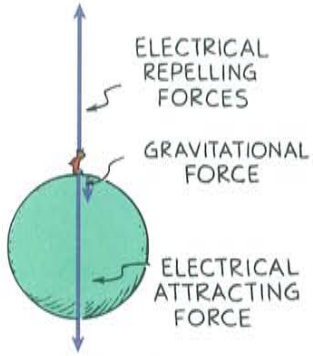


Figure 32.1 ▲
The enormous attractive and repulsive electrical forces between the charges in the earth and the charges in your body balance out, leaving the relatively weaker force of gravity, which attracts only. Hence your weight is due only to gravity.

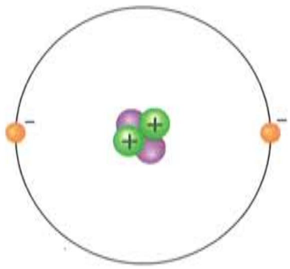


Figure 32.2 ▲
Model of a helium atom. The helium nucleus is composed of two protons and two neutrons. The positively charged protons attract two negative electrons.

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* Why don't protons pull the oppositely charged electrons into the nucleus? Interestingly enough, the reason is *not* the same as the reason that planets orbit the sun. Within the atom, different laws of physics apply. This is the domain of *quantum physics,* which we come to in Chapter 38. According to quantum physics, an electron behaves like a wave and has to occupy a certain amount of space related to its wavelength. The size of an atom is set by the minimum amount of "elbow room" that an electron requires.

Why is it that the protons in the nucleus do not mutually repel and fly apart? What holds the nucleus together? The answer is that in addition to electrical forces in the nucleus, there are even stronger forces that are nonelectrical in nature. These are *nuclear forces* and are discussed in Chapter 39.

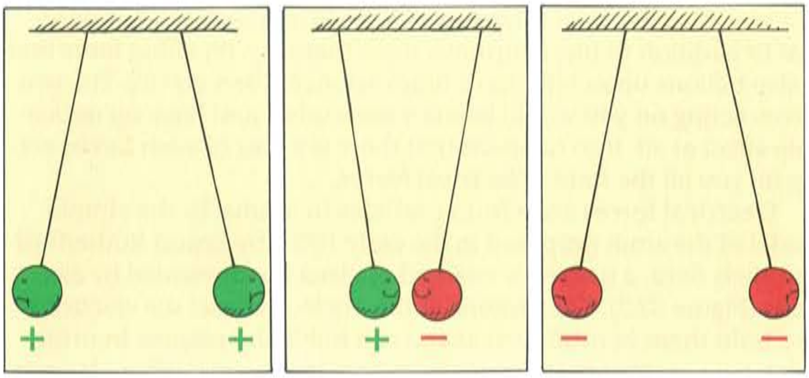

Figure 32.3 ▲
Likes repel and opposites attract.

and wagon to entertain people by demonstrating the scientific marvels of electricity. An important part of these demonstrations was the charging and discharging of pith balls. Pith is a light, spongy plant tissue that resembles Styrofoam, and balls of it were coated with aluminum paint so their surfaces would conduct electricity. When suspended from a silk thread, such a ball would be attracted to a rubber rod just rubbed with cat's fur, but when the two made contact, the force of attraction would change to a force of repulsion. Thereafter, the ball would be repelled by the rubber rod but attracted to a glass rod that had just been rubbed with silk. A pair of pith balls charged in different ways exhibited both attraction and repulsion forces (Figure 32.3). The lecturer pointed out that nature provides two kinds of charge, just as it provides two sexes.

Questions

1. Beneath the complexities of electrical phenomena, there lies a fundamental rule from which nearly all other effects stem. What is this fundamental rule?
2. How does the charge of an electron differ from the charge of a proton?

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nservation of charge

32.2 Conservation of Charge

Electrons and protons have electric charge. In a neutral atom, there are as many electrons as protons, so there is no net charge. The total positive charge balances the total negative charge exactly. If an electron is removed from an atom, the atom is no longer neutral. The atom has

Answers

1. Like charges repel; opposite charges attract.
2. The charges of both particles are equal in magnitude, but opposite in sign.

Science, Technology, and Society

The Threat of Static Charge

Two hundred years ago young boys called "powder monkeys" ran below the decks of warships to pick up sacks of black gunpowder for the cannons above. It was ship law that they do this task barefoot. Why? Because it was important that no static charge build up on their bodies as they ran back and forth. The bare feet ensured no build up of static charge that might result in an igniting spark.

Today electronic technicians in high-technology firms that build, test, and repair electronic circuit components similarly follow procedures to guard against static charge. Not because of any danger of blowing up their buildings, but to prevent damage to delicate circuits. Some circuit components are so sensitive that they can be "fried" by static electric sparks. So electronic technicians work in environments free of high-resistant surfaces where static charge can accumulate. They wear clothing of special fabric with ground wires between their sleeves and their socks. Some wear special wrist bands that are clipped to a grounded surface, so that any charge that builds up, by movement on a chair for example, is discharged. As electronic components become smaller and circuit elements are placed closer together, the threat of electric sparks producing short circuits becomes greater and greater. Maintaining a static-free environment is an important ongoing task for many companies.

one more positive charge (proton) than negative charge (electron) and is said to be positively charged.

A charged atom is called an *ion.* A *positive ion* has a net positive charge; it has lost one or more electrons. A *negative ion* has a net negative charge; it has gained one or more extra electrons.

Matter is made of atoms, and atoms are made of electrons and protons (and neutrons as well). An object that has equal numbers of electrons and protons has no net electric charge. But if there is an imbalance in the numbers, the object is then electrically charged. An imbalance comes about by adding or removing electrons.

Although the innermost electrons in an atom are bound very tightly to the oppositely charged atomic nucleus, the outermost electrons of many atoms are bound very loosely and can be easily dislodged. How much energy is required to tear an electron away from an atom varies for different substances. The electrons are held more firmly in rubber than in fur, for example. Hence, when a rubber rod is rubbed by a piece of fur, electrons transfer from the fur to the rubber rod. The rubber then has an excess of electrons and is negatively charged. The fur, in turn, has a deficiency of electrons and is positively charged. If you rub a glass or plastic rod with silk, you'll find that the rod becomes positively charged. The silk has a greater affinity

Conservation of charge is another of the conservation principles. Recall conservation of momentum and conservation of energy.

Point out to the students who have had chemistry that these definitions apply to the ions they studied.

Some students might be confused about the idea that more electrons make more negative charge if they think "excess" is positive and "take away" is negative. The negative of charge doesn't mean less. Electric charge could as well have been called "north" for electrons, and "south" for protons, similar to the naming of magnetic poles.

gure 32.4 ▲
ectrons are transferred from the r to the rod. The rod is then gatively charged. Is the fur arged? Positively or negatively?

for electrons than the glass or plastic rod. Electrons are rubbed off the rod and onto the silk. In summary:

> An object that has unequal numbers of electrons and protons is electrically charged. If it has more electrons than protons, the object is negatively charged. If it has fewer electrons than protons, then it is positively charged.

Notice that electrons are neither created nor destroyed but are simply transferred from one material to another. Charge is conserved. In every event, whether large-scale or at the atomic and nuclear level, the principle of **conservation of charge** applies. No case of the creation or destruction of net electric charge has ever been found. The conservation of charge is a cornerstone in physics, ranking with the conservation of energy and momentum.

Any object that is electrically charged has an excess or deficiency of some whole number of electrons—electrons cannot be divided into fractions of electrons. This means that the charge of the object is a whole-number multiple of the charge of an electron. It cannot have a charge equal to the charge of 1.5 or 1000.5 electrons, for example.* All charged objects to date have a charge that is a whole-number multiple of the charge of a single electron.

Question

If you scuff electrons onto your feet while walking across a rug, are you negatively or positively charged?

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ted, this film is excellent.
c Rogers' beautiful scientific
ilosophy is seen throughout
e film. It can be rented
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32.3 Coulomb's Law

Recall from Newton's law of gravitation that the gravitational force between two objects of mass m_1 and mass m_2 is proportional to the product of the masses and inversely proportional to the square of the distance d between them:

$$F = G\frac{m_1 m_2}{d^2}$$

where G is the universal gravitational constant.

The electrical force between any two objects obeys a similar inverse-square relationship with distance. This relationship was

Answer

You have more electrons after you scuff your feet, so you are negatively charged (and the rug is positively charged).

* Within the atomic nucleus, however, elementary particles called *quarks* carry charges 1/3 and 2/3 the magnitude of the electron's charge. Each proton and each neutron is made up of three quarks. Since quarks always exist in such combinations and have never been found separated, the whole-number-multiple rule of electron charge holds for nuclear processes as well.

discovered by the French physicist Charles Coulomb (1736–1806) in the eighteenth century. **Coulomb's law** states that for charged particles or objects that are small compared with the distance between them, the force between the charges varies directly as the product of the charges and inversely as the square of the distance between them. The role that charge plays in electrical phenomena is much like the role that mass plays in gravitational phenomena. Coulomb's law can be expressed as

$$F = k\frac{q_1 q_2}{d^2}$$

where d is the distance between the charged particles; q_1 represents the quantity of charge of one particle and q_2 the quantity of charge of the other particle; and k is the proportionality constant.

The SI unit of charge is the **coulomb,** abbreviated C. Common sense might say that it is the charge of a single electron, but it isn't. For historical reasons, it turns out that a charge of 1 C is the charge of 6.24 billion billion (6.24×10^{18}) electrons. This might seem like a great number of electrons, but it represents only the amount of charge that passes through a common 100-W lightbulb in about one second.

The proportionality constant k in Coulomb's law is similar to G in Newton's law of gravitation. Instead of being a very small number like G, the electrical proportionality constant k is a very large number. Rounded off, it equals

$$k = 9\ 000\ 000\ 000\ \text{N}\cdot\text{m}^2/\text{C}^2$$

or, in scientific notation, $k = 9.0 \times 10^9\ \text{N}\cdot\text{m}^2/\text{C}^2$. The units $\text{N}\cdot\text{m}^2/\text{C}^2$ convert the right-hand side of the equation to the unit of force, the newton (N), when the charges are in coulombs (C) and the distance is in meters (m). Note that if a pair of charges of 1 C each were 1 m apart, the force of repulsion between the two charges would be 9 billion newtons.* That would be more than 10 times the weight of a battleship! Obviously, such amounts of *net* charge do not exist in our everyday environment.

Demonstration: Show the class the enormous difference in strength between the forces of electricity and gravity. Use a charged comb to pick up a confetti-sized piece of paper. Now elaborate on what has happened. The huge earth with its gravitational force is pulling down on the paper. The small electric charge on the comb is pulling up on the paper. We have the huge earth vs. the small charge on the comb. It seems that the underdog, electricity, won. Stress that this is not true. The underdog is gravity, which is a billion billion times weaker than electricity. (Of course the force of electricity had the extra advantage of the smaller distance since both forces follow the inverse-square law.)

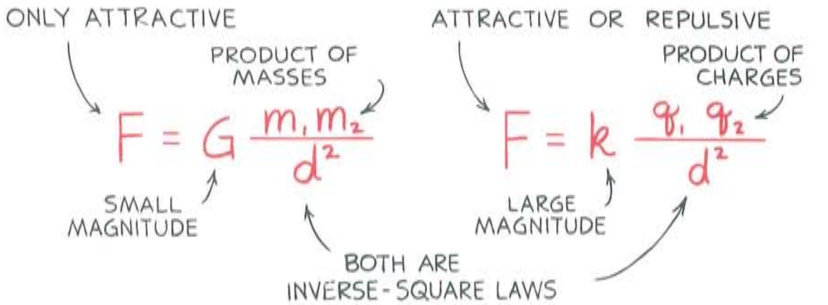


Figure 32.5
Comparison of Newton's law of gravitation and Coulomb's law.

* Contrast this with the gravitational force of attraction between two masses of 1 kg, each a distance 1 m apart: 6.67×10^{-11} N. This is an extremely small force. For the force to be 1 N, two masses 1 m apart would have to be about 122 000 kilograms each! Gravitational forces between ordinary objects are much too small to be detected except in delicate experiments. Electrical forces (noncanceled) between ordinary objects are large enough to be commonly experienced.

So Newton's law of gravitation for masses is similar to Coulomb's law for electric charges.* Whereas the gravitational force of attraction between a pair of one-kilogram masses is extremely small, the electrical force between a pair of one-coulomb charges is extremely large. The greatest difference between gravitation and electrical forces is that while gravity only attracts, electrical forces may either attract or repel.

Questions

1. What is the chief significance of the fact that *G* in Newton's law of gravitation is a small number and *k* in Coulomb's law is a large number when both are expressed in SI units?
2. a. If an electron at a certain distance from a charged particle is attracted with a certain force, how will the force compare at twice this distance?

   b. Is the charged particle in this case positive or negative?

Because most objects have almost exactly equal numbers of electrons and protons, electrical forces usually balance out. Between the earth and the moon, for example, there is no measurable electrical force. In general, the weak gravitational force, which attracts only, is the predominant force between astronomical bodies.

Although electrical forces balance out for astronomical and everyday objects, at the atomic level this is not always true. The negative electrons of one atom may at times be closer to the positive protons of a neighboring atom than to the average location of the neighbor's electrons. Then the attractive force between these charges is greater than the repulsive force. When the net attraction is sufficiently strong, atoms combine to form molecules. The chemical bonding forces that hold atoms together to form molecules are electrical forces acting in small regions where the balances of attractive and repelling forces is not perfect. It makes good sense for anyone planning to study chemistry to know something about electricity.

Answers

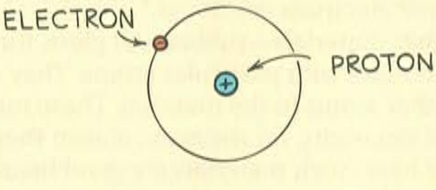
1. The small value of *G* indicates that gravity is a weak force; the large value of *k* indicates that the electrical force is enormous in comparison.
2. a. In accord with the inverse-square law, at twice the distance the force will be one-fourth as much.

   b. Since there is a force of attraction, the charges must be opposite in sign, so the charged particle is positive.

* The similarities between these two forces have made some physicists think they may be different aspects of the same thing. Albert Einstein was one of these people; he spent the later part of his life searching with little success for a "unified field theory." In recent years, the electrical force has been unified with the nuclear *weak force,* which plays a role in radioactive decay. Physicists are still looking for a way to unify electrical and gravitational forces.

Computational Example

The hydrogen atom has the simplest structure of all atoms. Its nucleus is a proton (mass 1.7×10^{-27} kg), outside of which there is a single electron (mass 9.1×10^{-31} kg) at an average separation distance of 5.3×10^{-11} m. Compare the electrical and gravitational forces between the proton and the electron in a hydrogen atom.



To solve for the electrical force, simply substitute the appropriate values in Coulomb's law.

$$\text{distance } d = 5.3 \times 10^{-11} \text{ m}$$

$$\text{proton charge } q_p = +1.6 \times 10^{-19} \text{ C}$$

$$\text{electron charge } q_e = -1.6 \times 10^{-19} \text{ C}$$

The electric force F_e is

$$F_e = k\frac{q_e q_p}{d^2}$$

$$= (9.0 \times 10^9 \text{ N·m}^2/\text{C}^2)\,\frac{(1.6 \times 10^{-19}\text{ C})^2}{(5.3 \times 10^{-11}\text{ m})^2}$$

$$= 8.2 \times 10^{-8} \text{ N}$$

The gravitational force F_g between them is

$$F_g = G\frac{m_e m_p}{d^2}$$

$$= (6.7 \times 10^{-11} \text{ N·m}^2/\text{kg}^2)\,\frac{(9.1 \times 10^{-31}\text{ kg})\,(1.7 \times 10^{-27}\text{ kg})}{(5.3 \times 10^{-11}\text{ m})^2}$$

$$= 3.7 \times 10^{-47} \text{ N}$$

A comparison of the two forces is best shown by their ratio:

$$\frac{F_e}{F_g} = \frac{8.2 \times 10^{-8}\text{ N}}{3.7 \times 10^{-47}\text{ N}} = 2.2 \times 10^{39}$$

The electrical force is more than 10^{39} times greater than the gravitational force. In other words, the electric forces that subatomic particles exert on one another are so much stronger than their mutual gravitational forces that gravitation can be completely neglected.

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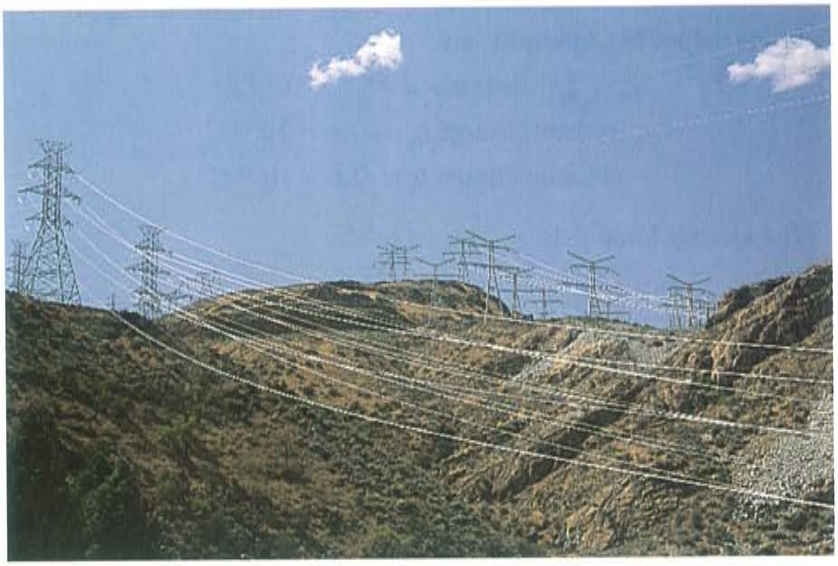
32.4 Conductors and Insulators

Electrons are more easily moved in some materials than in others. Outer electrons of the atoms in a metal are not anchored to the nuclei of particular atoms, but are free to roam in the material. Such materials are good **conductors.** Metals are good conductors for the motion of electric charges for the same reason they are good conductors of heat: Their electrons are "loose."

Electrons in other materials—rubber and glass, for example—are tightly bound and remain with particular atoms. They are not free to wander about to other atoms in the material. These materials are poor conductors of electricity, for the same reason they are generally poor conductors of heat. Such materials are good **insulators.**



ıure 32.6 ▶
easier for electric charge low through hundreds of meters of metal wire than ough a few centimeters of ılating material.

All substances can be arranged in order of their ability to conduct electric charges. Those at the top of the list are the conductors, and those at the bottom are the insulators. The ends of the list are very far apart. The conductivity of a metal, for example, can be more than a million trillion times greater than the conductivity of an insulator such as glass. In a power line, charge flows much more easily through hundreds of kilometers of metal wire than through the few centimeters of insulating material that separates the wire from the supporting tower. In a common appliance cord, charges will flow through several meters of wire to the appliance, and then through its electrical network, and then back through the return wire rather than flow directly across from one wire to the other through the tiny thickness of rubber insulation.

Whether a substance is classified as a conductor or an insulator depends on how tightly the atoms of the substance hold their electrons. Some materials, such as germanium and silicon, are good insulators in their pure crystalline form but increase tremendously in conductivity

when even one atom in ten million is replaced with an impurity that adds or removes an electron from the crystal structure. These materials can be made to behave sometimes as insulators and sometimes as conductors. Such materials are **semiconductors.** Thin layers of semiconducting materials sandwiched together make up *transistors,* which are used in a variety of electrical applications. How transistors and other semiconductor devices work will not be covered in this book.

At temperatures near absolute zero, certain metals acquire infinite conductivity (zero resistance to the flow of charge). These are **superconductors.** Since 1987, superconductivity at "high" temperatures (above 100 K) has been found in a variety of nonmetallic compounds. Once electric current is established in a superconductor, the electrons flow indefinitely. Explanations are presently being vigorously researched.

32.5 Charging by Friction and Contact

Demonstrate charging by contact.

Demonstration: In a completely darkened room, quickly pull the tape off a roll of friction tape in a way such that the class can see where the tape leaves the roll. The students should see sparks.

We are all familiar with the electrical effects produced by friction. We can stroke a cat's fur and hear the crackle of sparks that are produced, or comb our hair in front of a mirror in a dark room and see as well as hear the sparks of electricity. We can scuff our shoes across a rug and feel the tingle as we reach for the doorknob, or do the same when sliding across plastic seat covers while parked in an automobile (Figure 32.7). In all these cases electrons are being transferred by friction when one material rubs against another.

Figure 32.7 ▲
Charging by friction and then by contact while parked at a drive-in movie.

Electrons can be transferred from one material to another by simply touching. When a charged rod is placed in contact with a neutral object, some charge will transfer to the neutral object. This method of charging is simply called *charging by contact.* If the object is a good conductor, the charge will spread to all parts of its surface because the like charges repel each other. If it is a poor conductor, it may be necessary to touch the rod at several places on the object in order to get a more or less uniform distribution of charge.

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e can will roll toward the
d! Impressive.

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gure 32.8d, the charge distri-
tion is not uniform. Note

32.6 Charging by Induction

If we bring a charged object *near* a conducting surface, even without physical contact, electrons will move in the conducting surface. Consider the two insulated metal spheres, A and B, in Figure 32.8. In sketch (a), the uncharged spheres touch each other, so in effect they form a single noncharged conductor. In sketch (b), a negatively charged rod is held near sphere A. Electrons in the metal are repelled by the rod, and excess negative charge has moved onto sphere B, leaving sphere A with excess positive charge. The charge on the two spheres has been redistributed. A charge is said to have been **induced** on the spheres. In sketch (c), spheres A and B are separated while the rod is still present. In sketch (d), the rod has been removed. The spheres are charged equally and oppositely. They have been charged by **induction.** Since the charged rod never touched them, it retains its initial charge.

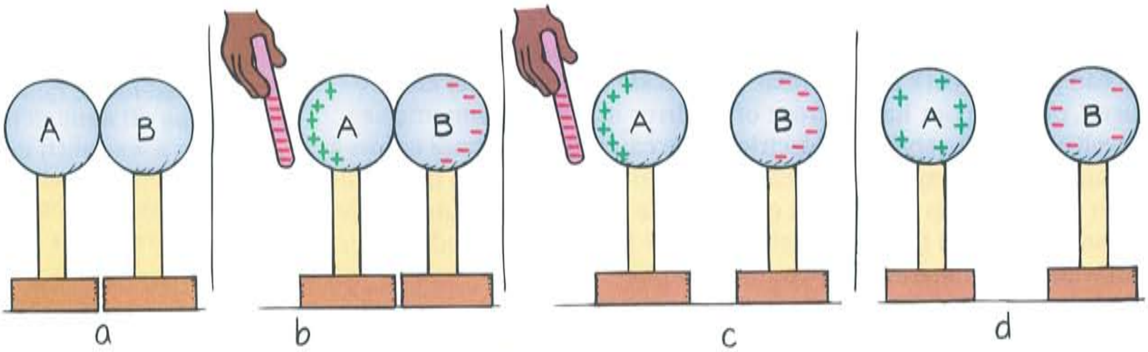

Figure 32.8 ▲
Charging by induction.

at the charges are closer
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lves of the conducting
heres. This is due to induc-
n. If the spheres were much
rther apart and induction
tween them were negligible,
e charge distribution on each
ould be uniform.

A single sphere can be charged similarly if we touch it when the charges are separated by induction. Consider a metal sphere that hangs from a nonconducting string, as shown in Figure 32.9. In sketch (a), the net charge on the metal sphere is zero. In sketch (b), a charge redistribution is induced by the presence of the charged rod. The net charge on the sphere is still zero. In sketch (c), touching the sphere

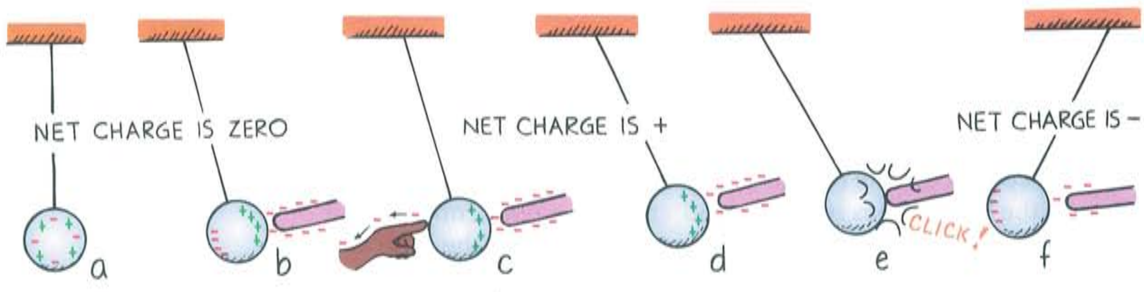


Figure 32.9 ▲
Charge induction by grounding.

removes electrons by contact. In sketch (d), the sphere is left positively charged. In sketch (e), the sphere is attracted to the negative rod; it swings over to it and touches it. Now electrons move onto the sphere from the rod. The sphere has been negatively charged by contact. In sketch (f), the negative sphere is repelled by the negative rod.

When we touch the metal surface with a finger (sketch (c)), charges that repel each other have a conducting path to a practically infinite reservoir for electric charge—the ground. When we allow charges to move off (or onto) a conductor by touching it, it is common to say that we are **grounding** it. Chapter 34 returns to this idea of grounding in the discussion of electric currents.

Questions

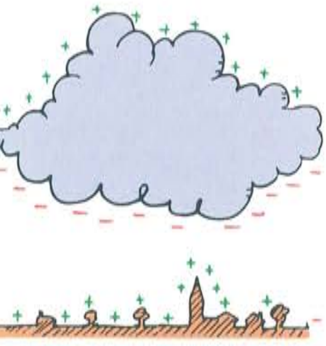
1. Would the charges induced on spheres A and B of Figure 32.8 necessarily be exactly equal and opposite?
2. Why does the negative rod in Figure 32.8 have the same charge before and after the spheres are charged, but not when charging takes place as in Figure 32.9?

Charging by induction occurs during thunderstorms. The negatively charged bottoms of clouds induce a positive charge on the surface of the earth below. Benjamin Franklin was the first to demonstrate this in his famous kite-flying experiment, in which he proved that lightning is an electrical phenomenon.* Most lightning is an electrical discharge between oppositely charged parts of clouds.

Answers

1. The charges must be equal and opposite on both spheres, because each single positive charge on sphere A is the result of a single electron being taken from A and moved to B. This is like taking bricks from the surface of a brick road and putting them all on the sidewalk. The number of bricks on the sidewalk will be exactly matched by the number of holes in the road. Similarly, the number of extra electrons on sphere B will exactly match the number of "holes" (positive charges) left in sphere A. Remember that the absence of an electron makes a positive charge.
2. In the charging process of Figure 32.8, no contact was made between the negative rod and either of the spheres. In the charging process of Figure 32.9, however, the rod touched the sphere when it was positively charged. A transfer of charge by contact reduced the negative charge on the rod.

* Benjamin Franklin was most fortunate that he was not electrocuted as were others who attempted to duplicate his experiment. In addition to being a great statesman, Franklin was a first-rate scientist. He introduced the terms *positive* and *negative* as they relate to electricity but nevertheless supported the "one-fluid theory" of electric currents. He also contributed to our understanding of grounding and insulation. As Franklin approached the height of his scientific career, a more compelling task was presented to him—helping to form the system of government of the newly independent United States. A less important undertaking would not have kept him from spending more of his energies on his favorite activity—the scientific investigation of nature.



gure 32.10 ▲
e bottom of the negatively
arged cloud induces a positive
arge at the surface of the
ound below.

portant Term

ectrically polarized

ow the effect of polarization
nen a charged balloon sticks
a wall.

The kind we are most familiar with is the electrical discharge between the clouds and the oppositely charged ground below.

Franklin also found that charge flows readily to or from sharp points, and fashioned the first lightning rod. If the rod is placed above a building connected to the ground, the point of the rod collects electrons from the air, preventing a large buildup of positive charge on the building by induction. This continual "leaking" of charge prevents a charge buildup that might otherwise lead to a sudden discharge between the cloud and the building. The primary purpose of the lightning rod, then, is to prevent a lightning discharge from occurring. If for any reason sufficient charge does not leak from the air to the rod, and lightning strikes anyway, it may be attracted to the rod and short-circuited to the ground, thereby sparing the building.

32.7 Charge Polarization

Charging by induction is not restricted to conductors. When a charged rod is brought near an insulator, there are no free electrons to migrate throughout the insulating material. Instead, there is a rearrangement of the positions of charges within the atoms and molecules themselves (Figure 32.11, left). One side of the atom or molecule is induced to be slightly more positive (or negative) than the opposite side. The atom or molecule is said to be **electrically polarized.** If the charged rod is negative, say, then the positive side of the atom or molecule is toward the rod, and the negative side of the atom or molecule is away from it. The atoms or molecules near the surface all become aligned this way (Figure 32.11, right).

This explains why electrically neutral bits of paper are attracted to a charged object. Molecules are polarized in the paper, with the oppositely charged sides of molecules closest to the charged object. Closeness wins, and the bits of paper experience a net attraction.

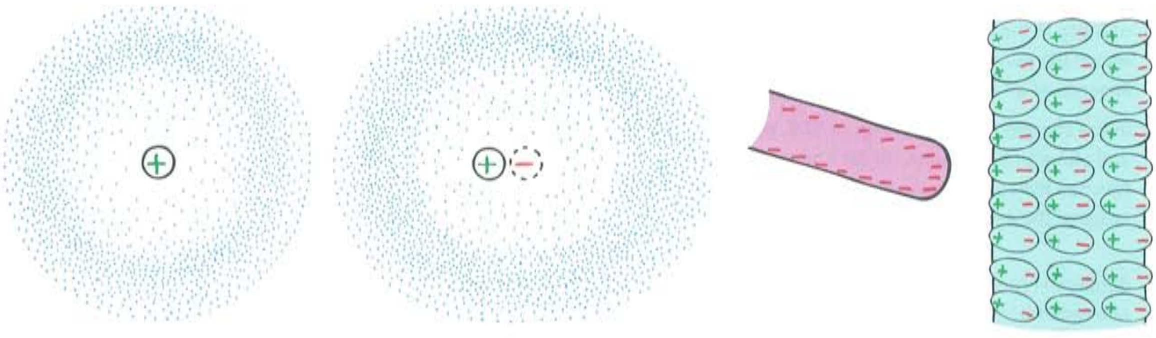


Figure 32.11 ▲
(Left) When an external negative charge is brought closer from the left, the charges within a neutral atom or molecule rearrange so that the left-hand side is slightly more positive and the right-hand side is slightly more negative. (Right) All the atoms or molecules near the surface become electrically polarized.

DOING PHYSICS

Charging

Charge a comb by running it through your hair. This will work especially well if the weather is dry. Now bring the comb near some tiny bits of paper. Explain your observations. Next, place the charged comb near a thin stream of running water from a faucet. Is there an electrical interaction between the comb and the stream? Does this mean the stream of water is charged? Why or why not?

Activity

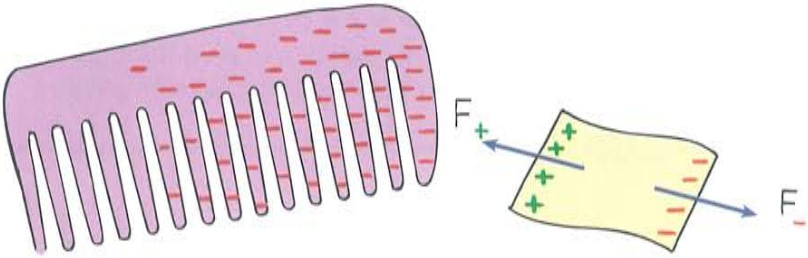


Figure 32.12 ▲
A charged comb attracts an uncharged piece of paper because the force of attraction for the closer charge is greater than the force of repulsion for the farther charge. Closeness wins, and there is a net attraction.

Sometimes they will cling to the charged object and suddenly fly off. This indicates that charging by contact has occurred; the paper bits have acquired the same sign of charge as the charged object and are then repelled.

Rub an inflated balloon on your hair and it becomes charged. Place the balloon against the wall and it sticks, because the charge on the balloon induces an opposite surface charge on the wall. Closeness wins, for the charge on the balloon is slightly closer to the opposite induced charge than to the charge of the same sign (Figure 32.13).

Many molecules—H_2O for example—are electrically polarized in their normal states. The distribution of electric charge is not perfectly even. There is a little more negative charge on one side of the molecule than on the other (Figure 32.14). Such molecules are said to be *electric dipoles.*

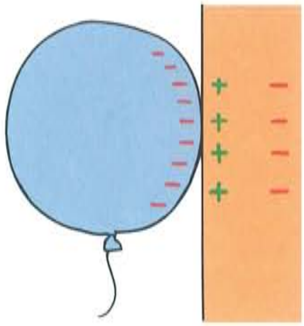
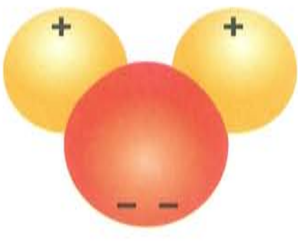


Figure 32.13 ▲
The negatively charged balloon polarizes molecules in the wooden wall and creates a positively charged surface, so the balloon sticks to the wall.



◀ **Figure 32.14**
An H_2O molecule is an electric dipole.

PHYSICS IN THE KITCHEN

Microwave Cooking

Imagine an enclosure filled with Ping-Pong balls among a few batons, all at rest. Now imagine the batons suddenly flipping back and forth like semi-rotating propellers, striking neighboring Ping-Pong balls. Almost immediately most Ping-Pong balls are energized, vibrating in all directions. A microwave oven works similarly. The batons are water molecules made to flip back and forth in rhythm with microwaves in the enclosure. The Ping-Pong balls are non–water molecules that make up the bulk of material being cooked.

H_2O molecules are polar, with opposite charges on opposite sides. When an electric field is imposed on them, they align with the field like a compass aligns with a magnetic field. When the field is made to oscillate, the H_2O molecules oscillate also—and quite energetically. Food is cooked by a sort of "kinetic friction" as flip-flopping H_2O molecules impart thermal motion to surrounding food molecules. A microwave oven wouldn't work without the presence of the polar molecules in the food. That's why microwaves pass through foam, paper, or ceramic plates with no effect.

In summary, we know that objects are electrically charged in three ways.

1. By friction, when electrons are transferred by friction from one object to another.
2. By contact, when electrons are transferred from one object to another by direct contact without rubbing. A charged rod placed in contact with an uncharged piece of metal, for example, will transfer charge to the metal.
3. By induction, when electrons are caused to gather or disperse by the presence of nearby charge (even without physical contact). A charged rod held near a metal surface, for example, attracts charges of the same sign as those on the rod and repels opposite charges. The result is a redistribution of charge on the object without any change in its net charge. If the metal surface is discharged by contact, with a finger for example, then a net charge will be left.

   If the object is an insulator, on the other hand, then a realignment of charge rather than a migration of charge occurs. This is charge polarization, in which the surface near the charged object becomes oppositely charged. This occurs when pieces of neutral paper are attracted to a charged object, or when you stick a charged balloon to a wall.

32 Chapter Review

For fuller explanations, see the TE notes in the front of this book.

Concept Summary

All electrons have the same amount of negative charge; all protons have a positive charge equal in magnitude to the negative charge on the electron.

- Electrical forces arise because of the way that like charges repel and unlike charges attract.
- Electric charge is conserved.
- According to Coulomb's law, the electrical force between two charged objects is proportional to the product of the charges and inversely proportional to the square of the distance between them.

Electrons move easily in good conductors and poorly in good insulators.

- Objects become charged when electrons move onto them or off of them.
- Charging by friction occurs when electrons are transferred by rubbing.
- Charging by contact occurs when electrons are transferred by direct contact.
- Charging by induction occurs in the presence of a charge without physical contact.
- Charge polarization occurs in insulators that are in the presence of a charged object.

Important Terms

charge (32.1)
conductor (32.4)
conservation of charge (32.2)
coulomb (32.3)
Coulomb's law (32.3)
electrical force (32.1)
electrically polarized (32.7)
electrostatics (32.0)
grounding (32.6)
induced (32.6)
induction (32.6)
insulator (32.4)
semiconductor (32.4)
superconductor (32.4)

Review Questions

Recall of key chapter ideas

1. Which force—gravitational or electrical—repels as well as attracts? (32.1) Electrical, gravitational only attracts
2. Gravitational forces depend on the property called *mass*. What comparable property underlies electrical forces? (32.1)
Charge
3. How do protons and electrons differ in their electric charge? (32.1) Opposite sign, but same magnitude
4. Is an electron in a hydrogen atom the same as an electron in a uranium atom? (32.1)
Yes, all electrons are identical.
5. Which has more mass—a proton or an electron? (32.1) Proton, more than 1800 times more mass
6. In a normal atom, how many electrons are there compared with protons? (32.1)
Same number, so net charge is zero
7. **a.** How do like charges behave?
Repel each other
b. How do unlike charges behave? (32.1)
Attract each other
8. How does a negative ion differ from a positive ion? (32.2) –ion has excess electrons, +ion has deficiency
9. **a.** If electrons are rubbed from cat's fur onto a rubber rod, does the rod become positively or negatively charged?
Negatively
b. How about the cat's fur? (32.2)
Positively, conservation of charge
10. What does it mean to say that charge is conserved? (32.2) Neither created nor destroyed, only transferred
11. **a.** How is Coulomb's law similar to Newton's law of gravitation? Both are inverse-square laws
b. How are the two laws different? (32.3)
One dep on m, one on q; Coul: attract *and* repel
12. The SI unit of mass is the kilogram. What is the SI unit of charge? (32.3)
Coulomb
13. The proportionality constant k in Coulomb's law is huge in ordinary units, whereas the proportionality constant G in Newton's law of gravitation is tiny. What does this mean in terms of the relative strengths of these two forces? (32.3) Electrical force relatively large

. Why does the weaker force of gravity dominate over electrical forces for astronomical objects? (32.3) Not diminished by repelling parts, large masses

. Why do electrical forces dominate between atoms that are close together? (32.3) Slight unbalance of attracting and repelling forces

. What is the difference between a good conductor and a good insulator? (32.4) Electrons free to move in good conductor

. **a.** Why are metals good conductors? Free electrons

b. Why are materials such as rubber and glass good insulators? (32.4) Bound electrons

. What is a semiconductor? (32.4) Material with adjustable cond, betw cond and insulator

. What is a superconductor? (32.4) Conductor with zero resistance

. **a.** What are the three main methods of charging objects? Contact, friction, induction

b. Which method involves no touching? (32.5–32.6) Induction

. What is lightning? (32.6) Elec discharge from cloud to cloud or to ground

. What is the function of a lightning rod? (32.6) To prevent discharge, also to guide to ground

. What does it mean to say an object is electrically polarized? (32.7) Negative on one side, positive on other

. When a charged object polarizes another, why is there an attraction between the objects? (32.7) Oppositely charged side a little closer

. What is an electric dipole? (32.7) Configuration equal + and − chgs at opposite ends

hink and Explain

Conceptual development through applied critical thinking

Electrical forces between charges are enormous relative to gravitational forces. Yet, we normally don't sense electrical forces between us and our environment, while we do sense our gravitational interaction with the earth. Why is this so? Charges can cancel, masses can't

2. By how much is the electrical force between a pair of ions reduced when their separation distance is doubled? Tripled? To 1/4; 1/9, by the inverse-square law

3. If you scuff electrons from your hair onto a comb, are you positively or negatively charged? How about the comb? You are negative, the comb is positive

4. An electroscope is a simple device. It consists of a metal ball that is attached by a conductor to two fine gold leaves that are protected from air disturbances in a jar, as shown in the sketch. When the ball is touched by a charged object, the leaves that normally hang straight down spring apart. Why? (Electroscopes are useful not only as charge detectors, but also for measuring the amount of charge: the more charge transferred to the ball, the more the leaves diverge.) Leaves have charges of like sign, which repel

5. Would it be necessary for a charged object to actually touch the leaves of an electroscope (see Question 4) for the leaves to diverge? Defend your answer. No, force acts thru empty space, can be charged by induction

6. If a glass rod that is rubbed with a plastic dry cleaner's bag acquires a certain charge, why does the plastic bag have exactly the same amount of opposite charge? Electrons simply transferred from one to the other

7. Why is a good conductor of electricity also a good conductor of heat? Both conductions are via free-moving electrons

8. Explain how an object that is electrically neutral can be attracted to an object that is charged. Charge induced, opp chgs closer than like chgs

9. If electrons were positive and protons negative, would Coulomb's law be written the same or differently? The same, likes still repel and unlikes attract

10. The five thousand billion billion freely moving electrons in a penny repel one another. Why don't they fly out of the penny? Electrons also attracted to protons in penny